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Modelling water quality in European rivers

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Abstract

An in-stream water quality model, QUESTOR (Quality Evaluation and Simulation Tool for River-systems), has been applied to rivers in Belgium, Finland and the United Kingdom as part of a study of the effects of climate change on the quality of freshwater resources in Europe. QUESTOR provides a flexible modelling framework that enables the assessment of alternative model structures based on different process representations. Results are presented from the application of a basic form of the model that includes a limited set of processes. The results for present-day simulations are good on all three catchments although the catchments have very different characteristics. However, the requirement for a more sophisticated model for simulations under possible future climatic conditions is identified.

1 Introduction

The management of river water quality is often facilitated by the use of in-stream water quality models. These models have a wide range of applications that include: providing a framework for the examination of inter-relationships between observed data; investigating water quality problems and developing remediation programmes; and exploring scenarios of change.

Many different models exist, some of which are suitable for more than one of these functions. However, a common feature of most of these models is that they require process rate parameter values to be adjusted for each application. These values may be based on theoretical understanding, laboratory studies, previous experience in applying the model, or calibration against local data. Once the parameter values have been set, the model can then be used to aid catchment management.

A possible weakness of this approach is when the model is to be used to explore scenarios representing conditions outside the range of those previously observed in the catchment, since the selected process rate parameter values may be inappropriate. Examples of such scenarios are changes in climate and land use, and it is necessary for any study of these impacts to ensure that suitable parameter values are selected. One way of increasing confidence in the use of a model for this purpose is to apply it to several catchments that together experience a wide range of existing conditions. This is the approach adopted by the Climate, Hydrochemistry and Economics of Surface-water Systems project (CHESS), which seeks to quantify impacts of climate and land use change on a set of European catchments.

2 Study Catchments

The study catchments used in CHESS come from Belgium (River Dender), Finland (River Vantaa), United Kingdom (River Ouse), Italy (River Enza) and Greece (River Pinios). The first three of these rivers are used in the analyses presented in this paper.

2.1 The River Ouse

The River Ouse is situated in northern England and drains to the east off the Pennine hills before flowing south-east through the Vale of York and into the Humber estuary. Several centres of population exist within the catchment, but the only major city is York, which is located some 10km above the tidal limit. The most downstream flow and water quality monitoring site is at Skelton, which is just upstream of York. At this point the drainage area is 3315km^2 and the mean flow is 48.97m^{3}s^{-1} (National Water Archive[1]). The upland areas of the catchment are used for rough grazing while the lower and flatter Vale of York is intensively cultivated, mainly for cereal production. The quality of the River Ouse is generally good upstream of York, but declines below the city, because of effluent discharges and low water velocities.

2.2 The River Dender

The River Dender is situated in central Belgium and is a tributary of the River Scheldt, which drains into the North Sea. The catchment area of the River Dender is 1384km^2 but the upper 677km^2 are represented as a tributary input to the model. The mean annual flow at the confluence with the Scheldt is $10m^3s^{-1}$ (Demuynck et al.[2]). The River Dender receives industrial wastewater (mainly food and textile processing) and diffuse pollution from agricultural activities. During extreme dry weather flow the discharge in the river consists mainly of wastewater and, coupled with high residence times, this results in a biologically dead river during some times of the year. Parts of the river are canalised with locks and sluices maintaining the water level which results in velocities close to zero during dry summer periods.

2.3 The River Vantaa

The River Vantaa is situated in southern Finland, north of Helsinki, and flows into the Gulf of Finland which is part of the non-tidal Baltic Sea. Approximately half of the catchment is forested and most of the remainder is intensively farmed, mainly for cereal production. The Vantaa drains an area of $1680km^2$ and has a mean annual flow of $17m^3s^{-1}$. High flow peaks usually occur in the spring time snow-melt period and in the autumn due to high rainfall. Because of the high proportion of clay soils, the water in the river is turbid throughout the year, and the high amounts of nutrients cause eutrophication and algal growth. The upper reaches of the River Vantaa receive the major point source discharges from municipal and industrial sewage treatment plants, which can cause the deterioration of water quality especially during low flow periods.

Table 1. Characteristics of the modelled river networks.

River	No. of reaches	No. of tributaries	Effluent points	No. of weirs	No. of water quality sites	Total Length (km)
Ouse	205	76	68	24	59	354.
Dender	55	11	21	7	3	49.
Vantaa	22	5	6	2	12	72.

3 In-stream water quality model

The in-stream water quality model QUESTOR (Quality Evaluation and Simulation Tool for River-systems) has been used to represent the three rivers. QUESTOR (Eatherall et al.[3]) has been developed in the UK from the earlier model QUASAR (Quality Simulation Along Rivers) described by Whitehead et al.[4]. Although it was developed primarily for UK applications it has been successfully applied elsewhere. QUESTOR is a reach-based model that has all effluent discharges, tributary inputs, and abstractions located at reach ends (i.e. there is no explicit representation of diffuse inputs directly to channels). It utilises a simple hydrodynamic routing scheme that is appropriate for the relatively long time step that is usually adopted (1 to 24 hours). The water quality component assumes perfect mixing within each reach (or sub-reach) but is flexible in allowing different process representations. As an initial attempt to model the rivers a basic set of processes was used that included re-aeration (in reaches and at weirs at reach ends), benthic oxygen demand, biochemical oxygen demand in the water column, nitrification and denitrification. The determinands represented were flow, temperature (modelled conservatively), dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonium (NH_4), and nitrate (NO_3).

The model was run in its time-series mode and therefore requires complete time series inputs for all tributaries, discharges and abstractions (the model can also operated in a stochastic mode that requires input distributions). These time series were prepared from observed data where possible, but elsewhere were either modelled using catchment information or constructed from analogue sites for which suitable data are available. In some cases default values had to be adopted (e.g. for unmonitored determinands from industrial discharges). Further details of the model application to each catchment is given in the next section.

Process rate parameters were initially set to default values that represented conservative transport plus aeration, and then adjusted based on comparisons between simulated and observed data at downstream sites.

4 Application of QUESTOR to the study catchments

The way in which QUESTOR has been applied to each of the catchments was dependent on both the characteristics of the catchments (described above) and the data availability, shown in Table 1. The data from the Ouse and the Vantaa were from routine water quality monitoring and enabled modelling for several years (5 and 6 respectively) using a model time step of one day. The data for the Dender were from three special sampling programmes each of one week duration, during which samples were taken every four hours.

Both the Vantaa and the Dender were represented by a single stretch of river, whereas the River Ouse was modelled using a network containing seven major tributaries, since data were available from many more sites. A summary of the network and input characteristics for the three rivers is shown in Table 2. The significance of point sources to the overall water quality of the catchments is indicated by considering the mean distance between effluent points, which is 3.7km for the Ouse, 2.3km for the Dender and 12.0km for the Vantaa. From this it may appear that the Ouse and Dender will have appreciably worse quality than the Vantaa. However, since the network for the Ouse extends high into the catchment where many of the point source discharges are small, the quality of the Ouse is in fact more similar to the Vantaa than the Dender.

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Table 2. Summary of input data

River	Period of data availability	Frequency of data sampling	Model time interval
Ouse	1986-1990	Daily, weekly and monthly.	1 day
Dender	1994	Four-hourly sampling for three one-week periods during 1994.	4 hours
Vantaa	1986-1991	Daily, weekly and monthly observed values, simulated daily flow data.	1 day

Within each model application parameters can be set individually for each reach, but in practice, without additional information, values are only adjusted between sites at which data are available for calibration. Goodness of fit was assessed using the interactive calibration tool within QUESTOR, which provides both a graphical display of simulated time series against the observed data and a "root mean square" error. For each catchment the calibration of the model was straightforward and generally good simulations of the modelled determinands were achieved. The range of parameters used for each of the rivers is given in Table 3. These are within the range found in previous applications of QUESTOR, and other comparable models.

Table 3. Summary of model parameters, all in day^{-1}

River	Denitrification	BOD rate	Nitrification	Benthic Oxygen demand rate
Ouse	< 0.05	< 0.1	< 0.1	0.0
Dender	< 0.5	0.1 - 0.5	< 2.0	<5.0
Vantaa	0.05	0.3	0.2	0.0

5 Results

The simulation and observed data for flow, DO, BOD, and NO_3 at a site on the lower River Ouse is shown in Figure 1. As already stated the simulation is seen to be generally good. At this site the river water quality is good with low values of BOD and NO_3 and high values of DO. In fact the DO values are at, or very close to saturation, for most of the period. The DO concentration is therefore largely dependent on temperature, with the higher summer temperatures resulting in lower DO concentrations.

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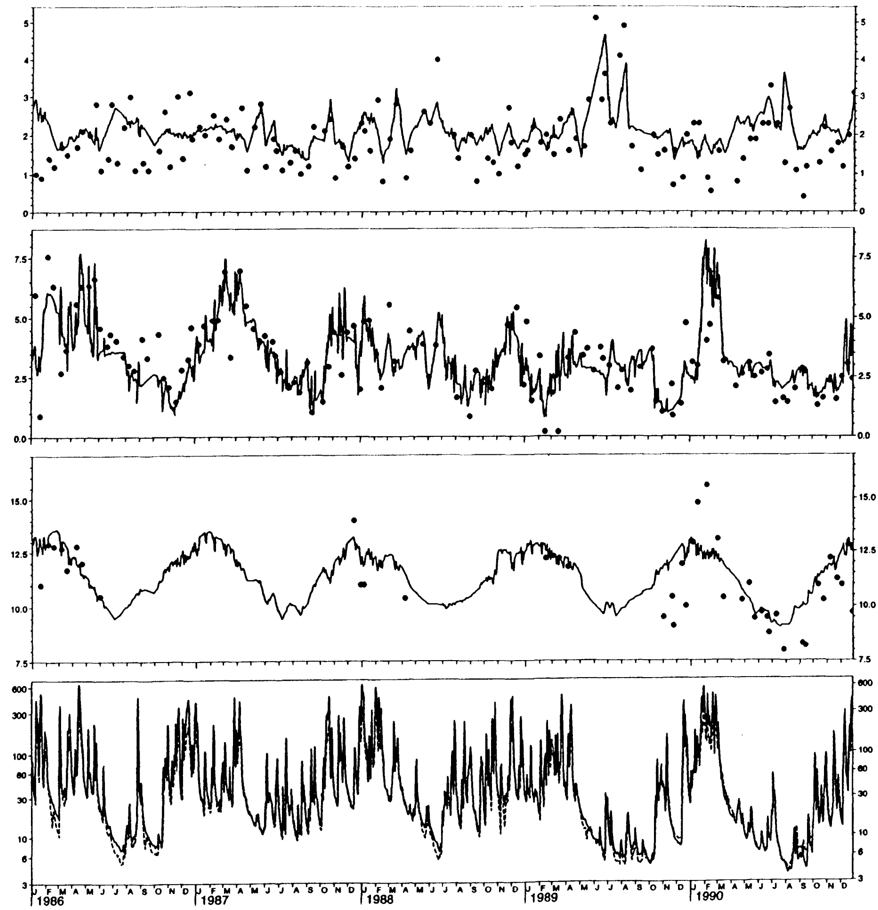

Figure 1: Water quality simulations (continuous line) and observed data (dashed line and dots) for the lower Ouse showing, from top to bottom, NO_3 (mg l^{-1}), BOD (mg l^{-1}), DO (mg l^{-1}, note the restricted range of the DO axis in this graph) and flow (m^3s^{-1}, shown on a log scale).

On the Vantaa a very similar variation in DO is seen with temperature again being the dominant influence on DO concentration (Figure 2a). In this case the temperature range is greater than on the Ouse and the DO variation more pronounced.

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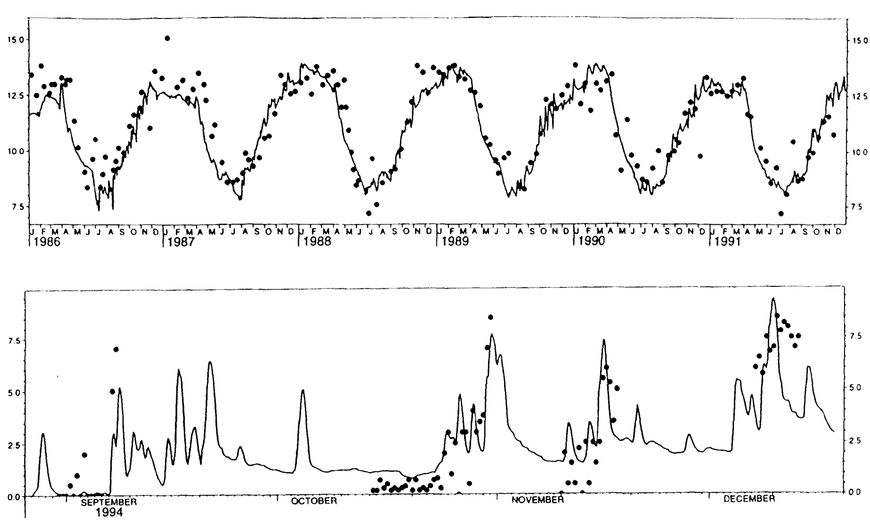

Figure 2: DO simulations (continuous line) and observed data (dots) on (a) the Rivers Vantaa, top, (note the restricted range of the DO axis in this graph) and (b) River Dender, bottom. Note that the figures use different time scales.

The Dender shows a very different variation in DO concentration (Figure 2b). The DO concentration is very close to zero for a seven day period in early September and remains generally lower for the rest of the period except during higher flow events. In this river during the summer months there is little aeration and DO is used to satisfy the BOD and in nitrification. Respiration and photosynthesis are considered important processes influencing DO levels in the Dender, but a reasonable simulation is produced with a model that does not include these processes. Using a version of the model in which these processes have been included, simulations show the expected diurnal DO. However, insufficient data were available to calibrate such a model with any confidence.

6 Discussion

The rather basic water quality model applied to the three catchments has given generally good simulations of the water quality in each case. The model parameters obtained from calibration against observed data are well within the range of previous model applications in the UK. Together these results can be taken to demonstrate the portability of the model to somewhat different environments (i.e. physical settings and anthropogenic influences). However, they also draw attention to what may be a weakness of this basic model in assessing climate change impacts.

In the Rivers Ouse and Vantaa the importance of temperature in influencing DO concentration has been noted. Under a different climate, any change in temperature will have a direct impact on the amount of oxygen available for in-stream process. If there is a general rise in summer temperatures, there will be a decrease in DO concentration because of this direct effect, but there may also be a secondary effect because flows will reduce through increased evaporation. In this case aeration may decrease because of lower water velocity, and longer residence times may enhance heating from solar radiation. While under present day conditions this direct heating can, seemingly, be ignored it is not apparent that this will be the case under a changed climate.

The role of primary production has also been identified as an uncertainty in present day representations of river systems. While it is possible to include photosynthesis and respiration as processes within the model, given the data currently available, it is difficult to calibrate such models and they cannot be applied with confidence for present day conditions. The use of the model to represent a situation in which one of the key controls of photosynthesis (solar radiation) changes, becomes problematic. It is hoped that this can be resolved by using additional data that represent these processes, and by applying the model to other catchments which currently experience drier and hotter weather in the summer months. The versatile modelling environment provided by QUESTOR will be used to identify a model structure that can be applied reliably to present day conditions, and also be used with confidence to simulate water quality when used with climate scenarios.

7 Conclusions

A water quality model has been found to give generally good simulations of present day water quality in three catchments in northern Europe. The process representation of this model is simple, and parameter values derived by calibration against observed data are comparable and compatible with earlier studies. However, theoretical arguments about the likely impacts of climate change suggest that this basic water quality model may not be used reliably to assess impacts of climate change and further research is required to identify a model structure that can be used reliably in this situation.

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